

**Final Report
Cooperative Agreement NCC5-622
Between NASA/Goddard Space Flight Center
and Cornell University**

February 15, 2002 – February 14, 2005

Radiative Studies of Planetary Atmospheres

Principal Investigator: Barney J. Conrath

The work accomplished during the period of this Cooperative Agreement was carried out as a joint effort between staff members of the Cornell University Center for Radiophysics and Space Research and the Laboratory for Extraterrestrial Physics of the NASA Goddard Space Flight Center.

Radiative Transfer Algorithm Development for Cassini CIRS

Retrieval algorithms and associated software for application to CIRS infrared spectral data have been developed and coded. A general forward radiative transfer code has been written that runs efficiently on a Macintosh, even at high spectral resolution (0.5 cm^{-1}). It makes use of the correlated-k approach for representation of the gaseous absorption and can include those gases listed in the HITRAN and GEISA atlases, along with collision-induced absorption. Cloud effects are included as spectrally dependent absorbers. Provision has been made for future extension to include particle scattering in an n-stream approximation. The primary purpose of the code is to produce synthetic data and to serve as the forward calculating element in gas and cloud retrieval programs developed for the Mac as well as other platforms.

Initial development of algorithms and production software suitable for application to CIRS data to be obtained from Jupiter, Saturn and Titan has been completed, and production versions of the software for application to the spectral data are in place. This includes temperature, gaseous constituent, and cloud opacity retrieval, algorithms that can be applied to both nadir and limb data.

This work has been done as a cooperative effort between Conrath and Matcheva (Cornell), Achterberg (GSFC/SSAI), and Flasar (GSFC).

Analysis of CIRS Jupiter Spectra

Retrievals of tropospheric and stratospheric temperatures and tropospheric ammonia have been carried out for all spectra obtained in the four ATMOS02 mapping sequences. The resulting derived data sets have been analyzed in an effort diagnostically study certain aspects of upper tropospheric dynamics. A detailed statistical analysis was made to examine possible correlations between upper tropospheric temperature fluctuations and ammonia fluctuations. To do this, it was necessary to implement a chi-square fitting approach that takes into account errors in both variables. The propagation of measurement errors through the non-linear inversion algorithms was established using a Monte Carlo approach. Strong anti-correlation was found between zonal mean temperatures and ammonia abundances, which is consistent with upward motions in the traditional zones and subsidence in the belts. However, no statistically significant correlation could be established between zonal structure in temperature and the ammonia mole fraction at most locations. The ammonia relative humidity fluctuations are correlated with temperature fluctuations, but this can be attributed to changes in the saturation vapor pressure with

temperature while the abundance remains essentially constant. Exceptions include the Great Red Spot where cold temperatures were found to be correlated with enhanced ammonia similar to that found in the zonal mean structure. The latitudinal variations of ammonia and temperature are found to be consistent with a linear relaxation-vertical advection model with an ammonia adjustment time constant of about 20% of the radiative time constant, and characteristic vertical velocities of ~ 0.2 scale heights per radiative time constant. This work is a collaborative effort between Gierasch and Conrath (Cornell) and Achterberg (GSFC/SSAI). The results of the effort have been submitted for publication (Achterberg, et al., 2005).

Progress has been made toward the quantitative retrieval of tropospheric cloud information on Jupiter using CIRS measurements. An algorithm has been developed that makes use of the spectral region between 1380 and 1400 cm^{-1} . In this region, the only significant gas absorption is H_2 and CH_4 , both of which can be assumed to have a known abundance. Windows in this region penetrate to depths greater than 1 bar in the absence of cloud opacity. Experiments with synthetic data indicate that information on cloud pressure level can be obtained, and for thin clouds, the total optical thickness can be retrieved. Application of the algorithm to CIRS data has been completed, and the results submitted for publication (Matcheva, et al., 2005). The possibility of using this approach on future Saturn data will be investigated, although the colder temperatures on Saturn make this application more challenging. This work is being carried out by Post-Doc Katia Matcheva, Conrath, and Gierasch (Cornell).

Conrath (Cornell) has participated in an investigation of the information content of CIRS Jovian spectra on stratospheric C_2H_2 and C_2H_6 . The investigation was led by Connor Nixon (GSFC/UMD). It was found

that essentially only one piece of information is available for each gas, necessitating the assumption of an a priori relative vertical profile. The results have been documented and submitted to a journal (Nixon, et al., 2005).

A comparison of Jovian thermal structure observed by Cassini CIRS (2001) with that obtained from Voyager IRIS (1979) has been made in a study led by Amy Simon-Miller (GSFC). Ground-based data have been used to establish a time series between the two epochs. The two sets of spacecraft data provide thermal structure with good resolution at two points in time while the ground-based data with limited vertical resolution establish a temporal baseline. The observed structure appears to be consistent with the proposed Quasi-Quadrennial Oscillation in the stratosphere, possibly penetrating down into the troposphere. High latitude stratospheric polar vortices are observed in both hemispheres. This work was carried out as part of collaboration between Simon-Miller, Conrath and Gierasch (Cornell), Flasar (GSFC), Achterberg (GSFC/SSAI), and Orton (JPL). The results have been submitted for publication (Simon-Miller, et al., 2005).

Meteorology of Hydrogen Atmospheres

A theoretical study of the effects of para hydrogen conversion on the meteorology of the upper tropospheres of the outer planets has been concluded. It has been found that the Ertel potential vorticity is not strictly conserved in the presence of hydrogen conversion, while the quasi-geostrophic potential vorticity is conserved to first order in the Rossby number. A paper documenting this work has been published (Gierasch, et al., 2003). Maps of potential vorticity are being constructed using retrievals from Voyager IRIS data, and a similar analysis has been initiated using

Cassini CIRS data. This aspect of the work is being documented in a companion paper.

This represents a collaborative effort between Gierasch and Conrath (Cornell), and Read (Oxford).

Analysis of CIRS Saturn Spectra

During the approach of Cassini to Saturn in June 2004, the southern hemisphere of Saturn was mapped by CIRS. These spectral data were inverted to obtain thermal structure in the upper troposphere and stratosphere. Zonal mean meridional cross sections of temperature were constructed, and gradient thermal winds were calculated. The equatorial jet of Saturn was found to decay monotonically into the stratosphere, unlike that of Jupiter. The results of this analysis were included in a CIRS team paper (Flasar, et al., 2005).

Work was initiated on the inference of the Saturn helium abundance by direct inversion of CIRS spectra. A far-IR map of the southern hemisphere of Saturn was employed. Preliminary results indicate a helium abundance consistent with that previously obtained by direct inversion of Voyager IRIS data but inconsistent with results previously obtained with an analysis using a combination of IRIS and radio science data. This work is a joint effort between Conrath and CIRS team member Daniel Gautier (Meudon).

Analysis of CIRS Titan Spectra

Temperature retrievals for the Stratosphere of Titan have been carried out using CIRS mapping data acquired during the T0 and Tb encounters. Quasi-zonal mean cross-sections have been constructed. Temperature

maxima are found at low latitudes with a strong pole ward gradient in the northern hemisphere and a weaker gradient in the southern hemisphere. Thermal winds calculated from the temperature cross sections indicate a strong eastward jet at mid-latitudes in the northern (winter) hemisphere. Because of the extended atmosphere of Titan, a revision to the traditional thermal wind equation was found to be necessary, with the wind gradient evaluated along cylindrical surfaces parallel to the rotation axis of the planet. This work was carried out by Gierasch and Conrath (Cornell) and Flasar and Achterberg (GSFC).

Far-IR rotational lines of CH₄ in the CIRS spectra of Titan have been used to determine the stratospheric methane abundance, found to be approximately 2%. This work involved a collaboration between Conrath (Cornell), Achterberg (GSFC), and Bezard (Meudon). These results are to be incorporated into a CIRS team paper on early Titan results to be submitted to *Science*.

Cassini Saturn and Titan Mission Planning

Support for the mission planning activity for Saturn and Titan observations has continued. The effort has focused primarily on the Saturn and Titan atmospheric observations that are included in the “rings segments” of the Cassini orbits. Assistance has been provided in the detailed definitions of the various atmospheric observations.

Publications

Achterberg, R.K., B.J. Conrath, P.J. Gierasch, and F.M. Flasar 2005.

Cassini CIRS retrievals of temperature and ammonia in Jupiter's upper troposphere. *Icarus*, submitted.

- Flasar, F.M., B.J. Conrath, et al. 2004. An intense stratospheric jet on Jupiter. *Nature*, **247**, 132-135.
- Flasar, F.M., R.K. Achterberg, B.J. Conrath, et al. 2005. Temperatures, winds, and composition in the Saturn system. *Science*, in press.
- Gierasch, P.J., B.J. Conrath, and P.L. Read 2004. Non-conservation of potential vorticity in hydrogen atmospheres. *J. Atmos. Sci.*, **61**, 1953-1965.
- Matcheva, K.I., B.J. Conrath, P.J. Gierasch, and F.M. Flasar 2005. Cloud structure of the Jovian atmosphere as seen by the Cassini/CIRS experiment. *Icarus*, submitted.
- Nixon, C.A., R.K. Achterberg, B.J. Conrath, et al. 2005. Meridional variations of C_2H_2 and C_2H_6 in Jupiter's atmosphere from Cassini CIRS infrared spectra 2005. *Icarus*, submitted.
- Simon-Miller, A.A., B.J. Conrath, P.J. Gierasch, G.S. Orton, R.K. Achterberg, F.M. Flasar, and B. Fisher 2005. Jupiter's atmospheric temperatures: From Voyager IRIS to Cassini CIRS. *Icarus*, submitted.